AD 745004

Final Report
Period Covered: 21 June 1972 - 15 February 1972
Program Code No. 6A610
Scientific Officer: Dr. Robert G. Morris

Sponsored by
Advanced Research Projects Agency
ARPA Order No. 1920

Principal Investigator: Marion Todd
(213) 449-6400 Ext. 225

Tetra Tech, Inc.

THREE-COLOR INFRARED RADIOMETER

Prepared by: Marion Todd and Willard Wells

July 1972

This research was supported by the Advanced Research Projects Agency of the Department of Defense and was monitored by ONR under Contract No. N00014-72-C-0015.

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FIGURES AND TABLES

SUMMARY

Tetra Tech has designed, constructed and calibrated a three-color infrared radiometer, intended primarily for examining the thermal radiance from the sea with maximum sensitivity for small temperature differences. The radiometer operates in wavelength bands matched to the three most transparent atmospheric windows in the infrared, namely 2.3, 3.8, and 10 microns. Its thermal sensitivity in the two longer-wavelength bands equals the expected mean background thermal noise level.

The radiometer measures radiant intensity in each band at a rate of 40 samples per second. Each of these measurements is compared to an internal reference blackbody, a total of six measurements 40 times per second. Occasionally on command, the radiometer looks at an external blackbody through the same optics that it sees its field of view. This information permits calibration of the data in absolute temperature units. The system includes an electronic processor that digitizes the radiometric data along with time and calibration information and stores them on magnetic tape in a form compatible with standard digital systems. In addition to the hardware, Tetra Tech has developed the software to read the tapes and process and display the data.

The radiometer was developed for an experiment to detect internal ocean waves through their radiometric effects. These are gravity waves between temperature strata of the ocean, i.e., the isotherms move up and down in wave motions, but not the sea surface. These waves influence the sea surface with zones of convergent

and divergent flow, which in turn influence infrared radiance either through wave mechanics and wave slopes or through compaction and dilation of surface contaminants and their effects on temperature. The experiment is situated on the NUC tower off San Diego, where strong natural internal waves produce visible slicks.

There is one detector for each wavelength, and each looks through the same 5 cm^2 aperture and sees the same field of view which may be set between .02 to 0.2 radian angular diameter. This narrow field of view may be scanned at rates from 0 to 3 radians per second through an angle as large as 150^o. The scans may be oriented in various ways to give a variety of modes of operation, some of which include the horizon and sky. Sky scans are often important to correct for sky radiance which is reflected in the water surface (reflection $\approx$ 1%).

The system has the following physical characteristics:

Radiometer: 30 lbs., 8" diameter, 23" long
Scanner Attachment: 12 lbs., 7.25" diameter, 9" long
Console and Data Storage System: 5'6" high, 23" wide, 26" deep

The blackbody temperature references have the following accuracies:

Long term absolute accuracy - 10^{-2} K
Short term stability accuracy - 10^{-3} K

The infrared bands have the following individual properties:

Wavelength Band	2.19-2.41 μm	3.53-4.11 μm	9.99-11.1 μm
Detector Material	InSb	InSb	Ge:Hg
Coolant	Liq. N_2	Liq. N_2	Liq. He
Noise Equivalent Temperature			
.2 radians	2×10^{-2}	5×10^{-4}	5×10^{-4}
.02 radians	<1.0	$<10^{-2}$	$<10^{-2}$

In addition to the summary description above, the report describes scan modes, console displays, and calibration in detail.

FINAL REPORT TC-243

Three-Color Infrared Radiometer

Pursuant to ARPA order No. 1920/06-22-71 and ONR Contract No. N0014-72-C-0015, Tetra Tech has designed, constructed, and calibrated a three-color infrared radiometer intended primarily for examining the thermal radiation of the sea with maximum sensitivity for small temperature differences. The radiometer operates in wavelength bands matched to the three most transparent atmospheric windows in the near and middle parts of the infrared spectrum. Its thermal sensitivity in the two longer-wavelength bands equals the expected mean background thermal noise level. The radiometer, its scan unit, and console with data processor are shown in the photograph of Fig. 1.

The radiometer measures radiant intensity in each band at a rate of 40 samples per second. Each of these measurements is compared to an internal reference blackbody to give a total of six measurements 40 times per second. Occasionally on command, the radiometer looks at an external blackbody through the same optics that it sees its field of view. This information permits calibration of the data in kelvins (^{o}C) for easy comparison to other environmental data. The radiometer system includes an electronic processor that digitizes the radiometric data along with time and calibration information and stores them on magnetic tape in a form compatible with IBM, CDC, and other standard digital systems (7-track, 800 bits per inch). To minimize RFI problems, the data are digitized inside the radiometer head before transmission to the console/processor and tape recorder. In addition to the hardware, Tetra Tech has also developed the software to read the tapes and process and display the data.

The three-color radiometer was developed for an experiment on the NUC tower situated about a mile off the coast of San Diego. The


INFRARED RADIOMETER

experiment will study internal gravity waves, waves contained entirely within the water that are analogous to surface gravity waves except that the two media involved are not air and water but both water at two different temperatures. The experiment will look for any temperature or other radiometric clues to internal gravity waves and will aid in identifying mechanisms by which internal waves couple to radiometric observables at the surface of the water. The tower is located in a region where strong internal waves occur naturally, and their strong coupling to surface phenomena produces visible slicks.

1.0 MODES OF OPERATION

The radiometer is constructed for a variety of modes of operation looking and scanning in different directions depending on the internal wave coupling mechanism under test, the sun angle, and concurrence with another radiometric experiment by Scripps Institution of Oceanography, and sky conditions. One way of classifying the modes is as follows:

A. Thermometer mode--downlooking.
   1. North Offset
      a. Scanning
      b. Staring
   2. West Offset
      a. Scanning
      b. Staring

B. Wave-slope mode--near horizon.
   1. Vertical scan
   2. Horizontal scan
   3. Staring

The subdivisions of the two basic modes require some further explanation:

Thermometer mode, north offset (A1)

This is the mode indicated as a down-looking east-west scan in Fig. 2. The main purpose is to stare at or scan across the spot where the SIO radiometer looks. When SIO is not running, there will often be advantages in switching to A2, the west offset.

Thermometer mode, west offset (A2)

This mode consists of the extreme ends of the vertical and sky scan shown in the figure. Most of the time the radiometer will stare or execute a small scan at the lower end (down-looking), but as often as necessary the operator will slew to the sky end and stare or execute a corresponding small scan over the portion of the sky that the radiometer sees reflected in the water. The advantage of this mode is that it scans the reflected sky on command of the operator at the console without having to dismount the radiometer head. In this respect the west offset mode is similar to the SIO radiometer. When the sky is complex and rapidly changing, this will be the principle mode of operation.

Wave-slope mode

The horizontal scan is illustrated in the figure, and the vertical scan is only a small part of the maximum vertical scan shown in the figure, a sector that begins 20 to 30 degrees below the horizon and may include the horizon and a similar sector of sky.

Sky scans at the water-reflectance angle will be made periodically with reduced sensitivity during all modes of operation to determine if any of the radiometric structure of the sky is contributing significantly to the observed signal.

2.0 SYSTEM DESCRIPTION

The optical paths for each of the three bands are illustrated schematically in Fig. 3. The three detectors for the three bands share the scan

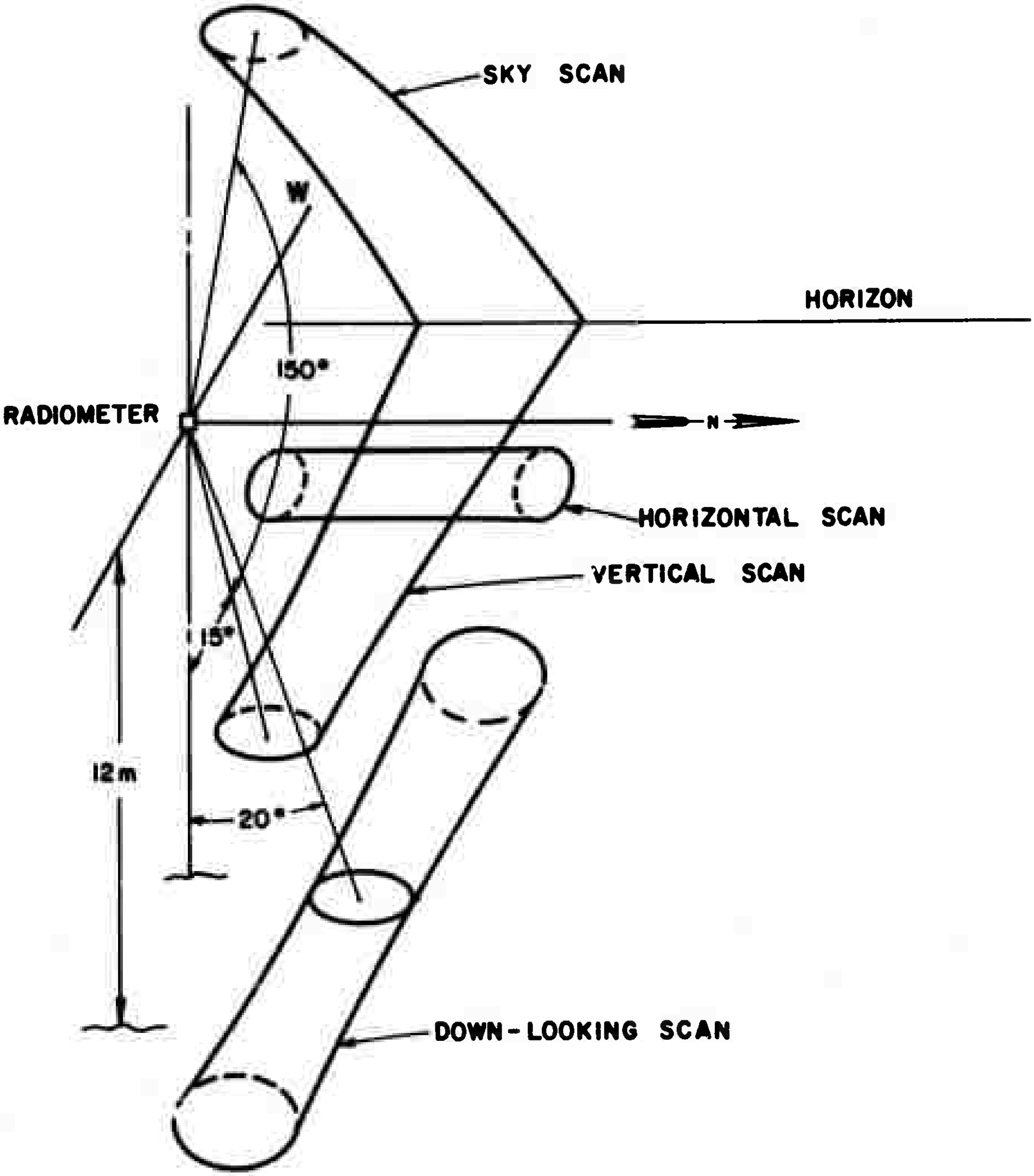


Fig. 2 Tetra Tech Radiometer Modes

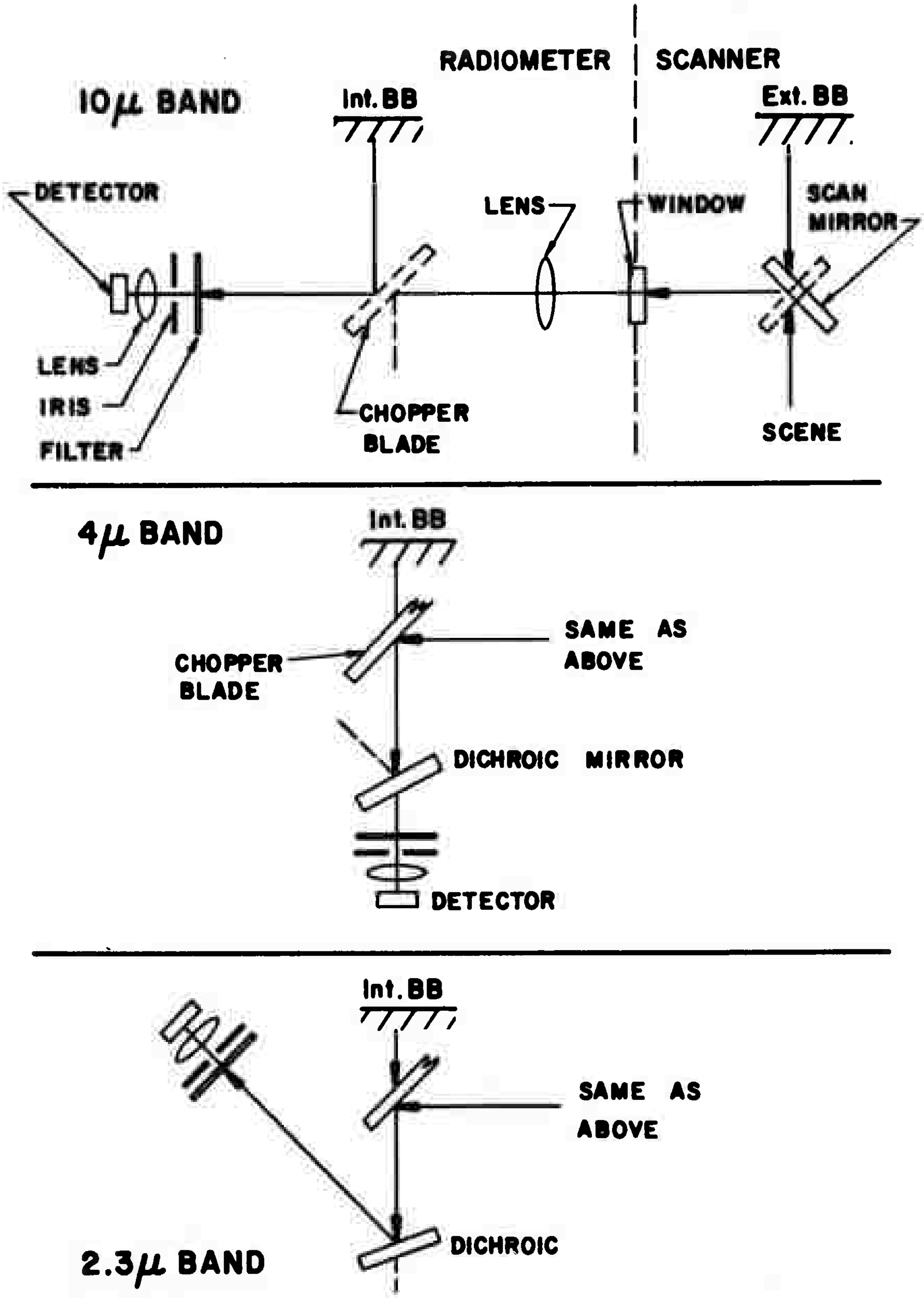


Fig. 3 Optical Paths For Three Wavelength Bands

mirror, germanium window, the aperture stop, and the germanium objective lens. The two shorter-wavelength optical paths are separated from the 10 μm path by the front surface of an optically flat gold-plated cold chopper mirror. The paths for the two shorter wavelengths are then separated by a dichroic mirror, which reflects 98% in the 2.3 μm band and transmits approximately 95% in the 3.8 μm band. After beam separation, each beam passes through a variable diameter field stop, a germanium field lens, and the filter that bounds the wavelength pass-band, before reaching the detector. The germanium optical components are anti-reflection coated to transmit the 2.3, 3.8, and 10 μm wavelength bands.

Fig. 4 and Fig. 5 show the radiometer and its scanner in detail. The radiometer uses all cold optics to reduce the background photon reflux and to suppress the calibration drift usually found in systems that employ ambient-temperature optics. The system aperture is 2.5 cm in diameter. The entrance aperture stop is imaged onto the face of each detector to ensure that the response of the system is not affected by variable responsivity across the face of the detector. The entire optical system is located in a nitrogen Dewar to maintain a uniform 78 K temperature. The mercury doped germanium detector for the 10 μm band is cooled to 4.2 K by a liquid helium Dewar that is surrounded by a 78 K shell. The entire cold-optical/Dewar system is suspended in a vacuum shell by means of a 0.012 inch rigid, stainless steel hoop truss. The internal radiometric reference level is obtained by alternately viewing a servo-controlled internal blackbody reference. Calibration of the radiometer, including all optical components, is accomplished by looking into an external servo-controlled blackbody reference contained in the scanner unit. The blackbodies are controlled to better than ±0.001 K stability. Summary characteristics of the system are listed in Table I.

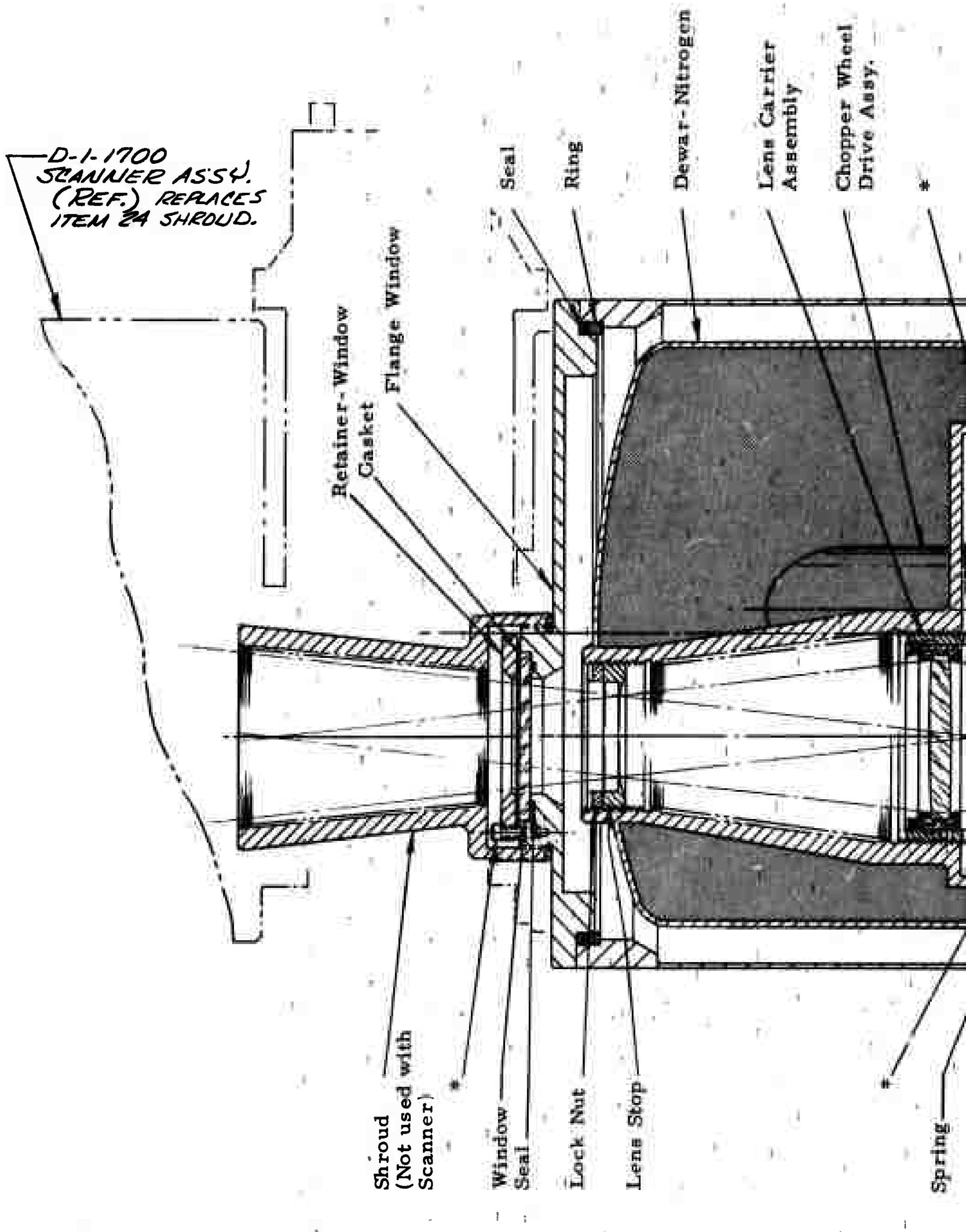
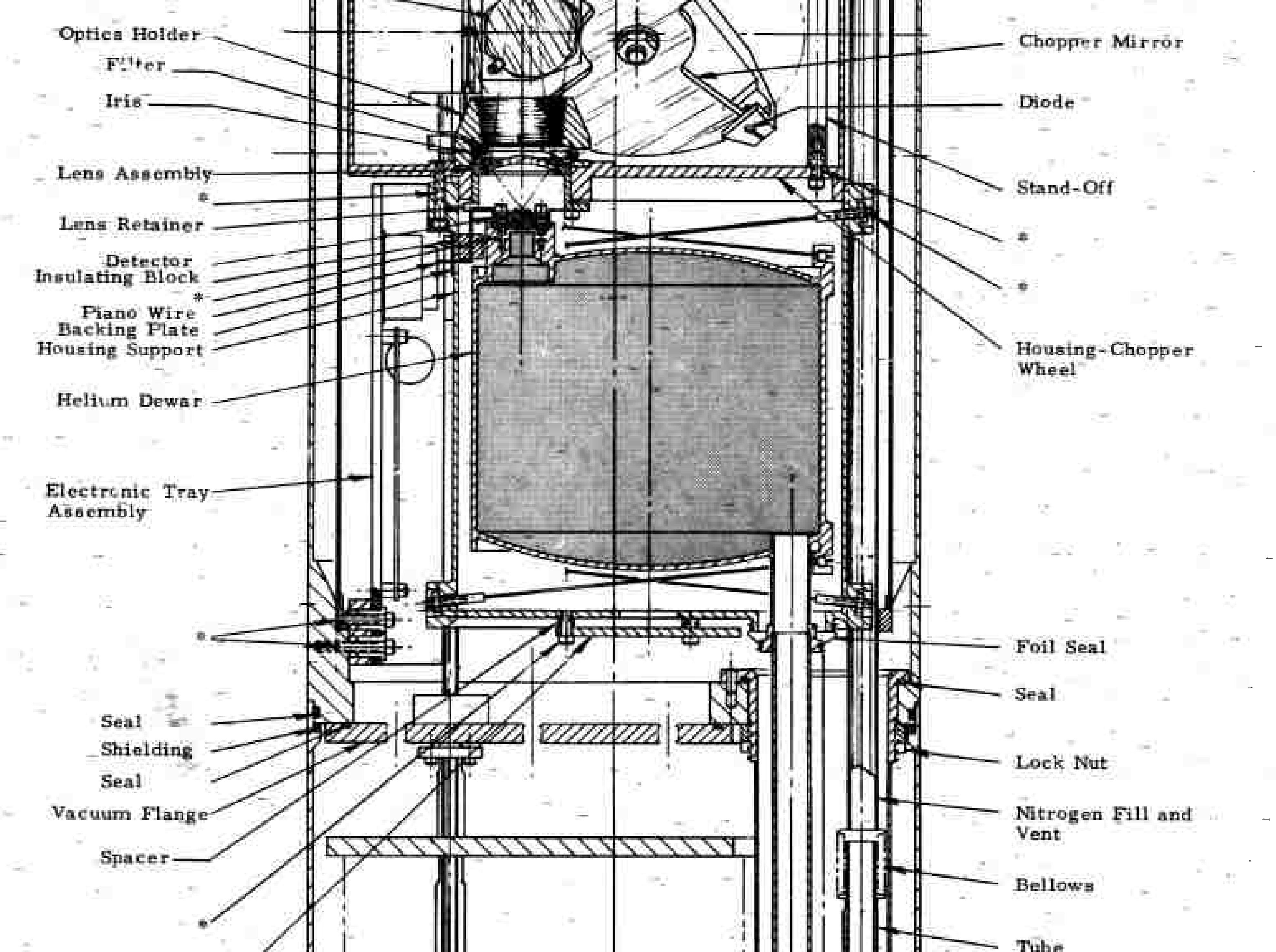
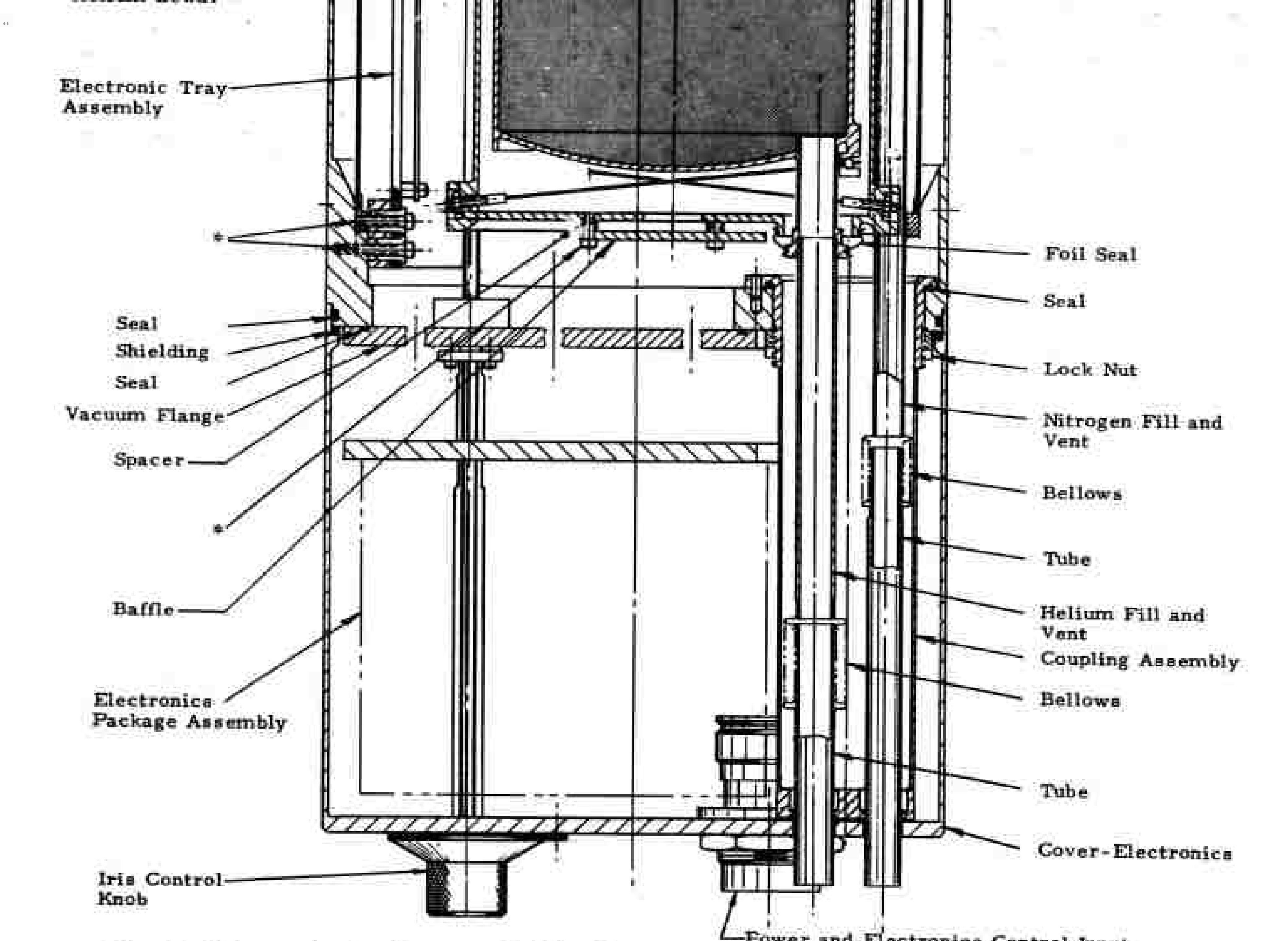


Fig. 4 Tetra Tech Three-Color Infrared Radiometer



Optics Holder
Filter
Iris
Lens Assembly
*
Lens Retainer
Detector
Insulating Block
*
Piano Wire
Backing Plate
Housing Support
Helium Dewar
Electronic Tray
Assembly
*
Seal
Shielding
Seal
Vacuum Flange
Spacer
*
Chopper Mirror
Diode
Stand-Off
*
*
Housing-Chopper
Wheel
Foil Seal
Seal
Lock Nut
Nitrogen Fill and
Vent
Bellows
Tube



Electronic Tray Assembly
*
Seal
Shielding
Seal
Vacuum Flange
Spacer
*
Baffle
Electronics Package Assembly
Iris Control Knob
Foil Seal
Seal
Lock Nut
Nitrogen Fill and Vent
Bellows
Tube
Helium Fill and Vent
Coupling Assembly
Bellows
Tube
Cover-Electronics
Power and Electronics Control Input

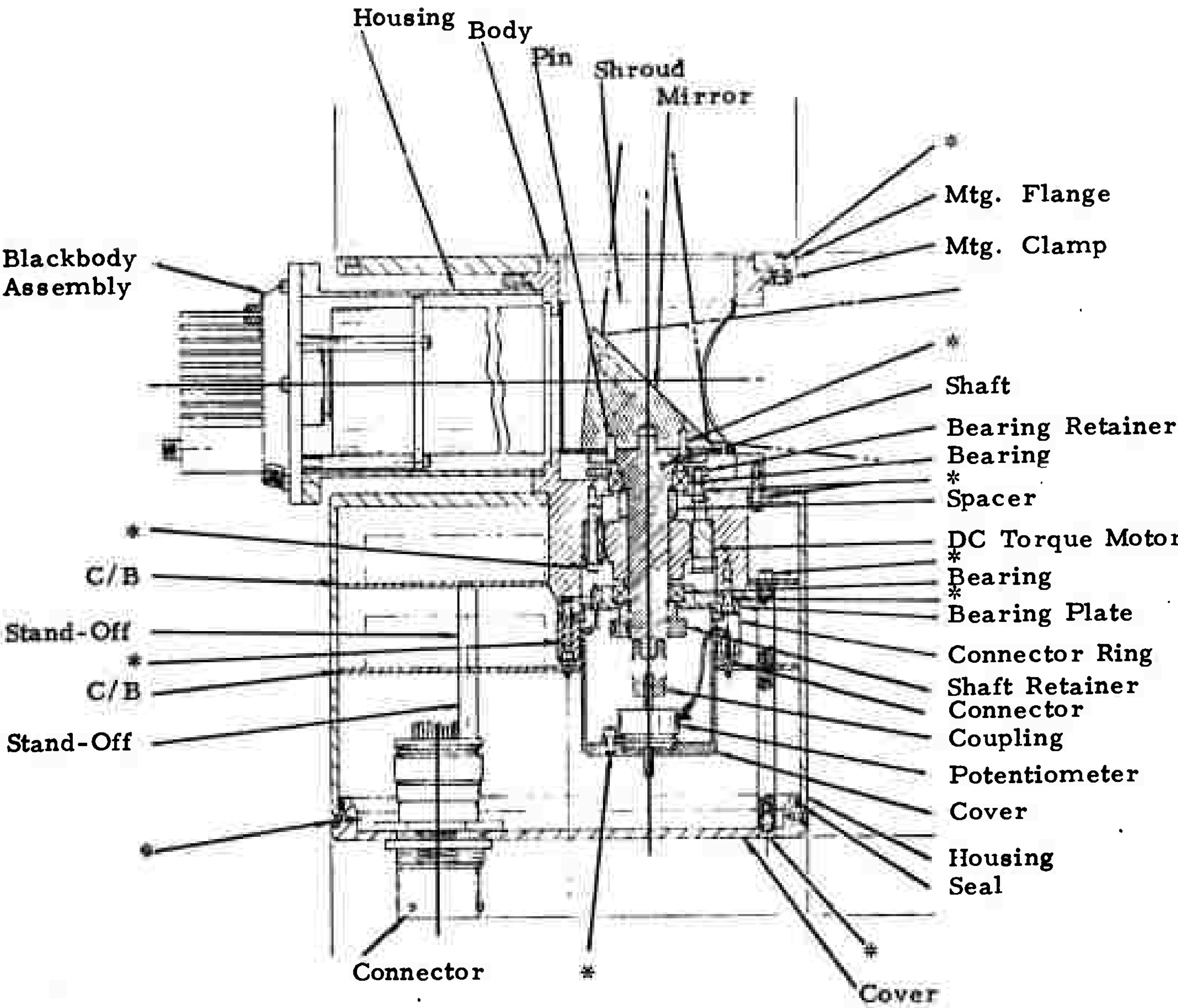


Fig. 5 Scanner Assembly for Radiometer (Fig. 4)

*Screws

TABLE I

TETRA TECH THREE-COLOR RADIOMETER
SUMMARY SPECIFICATIONS

Wavelength Band	2.19-2.41 μm	3.53-4.11 μm	9.99-11.1 μm
Detector Material	InSb	InSb	Ge:Hg
Detectivity (D*, $cmHz^{\frac{1}{2}} w^{-1}$)	1.0×10^{12}	2×10^{12}	$>10^{11}$
Aperture Area	5 cm^2	5 cm^2	5 cm^2
Noise Equivalent Flux Density (NEFD, $w\ cm^{-2}$)	$<10^{-12}$	$<10^{-12}$	$<10^{-11}$
Instantaneous Field Diameter in Radians	0.02-0.2	0.02-0.2	0.02-0.2
Noise Equivalent Temperature Change (NEΔT, ^{o}C)			
0.2 radians field diameter	2×10^{-2}	5×10^{-4}	5×10^{-4}
0.02 radians diameter	<1.0	$<10^{-2}$	$<10^{-2}$
Scanned Swath Width	0-150^{o}	0-150^{o}	0-150^{o}
Scan Rate	0-3 rad/sec	0-3 rad/sec	0-3 rad/sec

DATA PROCESSING

Data Storage	Digital Tape
Data Resolution	15 Significant Bits
Max Dynamic Range	± 12 K Coded in 18 Bits
Data Rate (for 12-Hour Tape)	18 Bit Resolution, 40 words/sec

(continued)

TABLE I (CONTINUED)

BLACKBODY CHARACTERISTICS

Calibration Rate	
Internal (Radiometric Reference)	1 per Instantaneous Field of View
External (Thermal Calibration)	On Command

	Internal	External
Readout Resolution Digital (On Tape)	10^{-3} K	10^{-3} K
Readout Accuracy (Long Term)	$<10^{-2}$ K	$<10^{-2}$ K
Stability, Short Term	$\pm 1 \times 10^{-3}$ K	$\pm 1 \times 10^{-3}$ K
Long Term Drift	$<10^{-2}$ K	$<10^{-2}$ K

PHYSICAL CHARACTERISTICS

Radiometer	Weight:	30 Pounds
	Size:	8 Inches Diameter
		23 Inches Long
Scanner	Weight:	12 Pounds
	Size:	7.25 Inches Diameter
		9 Inches Long
Console and Data Storage System	Size:	5 Feet, 6 Inches High
		23 Inches Wide
		26 Inches Deep

Digital Data Storage System is Contained in One 60 x 19 Inch Rack

3.0 CONSOLE DISPLAYS

The display units described here were not required under the ONR contract, and the work was performed after the expiration of that contract. Nevertheless, the description is included as a courtesy to inform the reader of the present status of the system. Two different display units show the operators what is happening in real time. Tha analog unit shows differential radiant intensity as a function of both scan position and time (successive scans), while the digital unit displays any of several types of digital information going onto magnetic tape.

3.1

The analog display unit generates real-time displays of radiometric data from the three separate wavelength channels. Fifteen to twenty minutes (360 scans) of data are presented in three horizontal bars on the face of an oscilloscope. Each bar represents a detector; i.e., it is intensity-modulated by the detector signal. Each sweep of the radiometer scanner corresponds to one vertical oscilloscope trace in each of the three channels. Three hundred-sixty vertical sweeps terminate a (single) horizontal sweep, which is recorded on film.

The displayed signal is the difference between the signals from the field of view and from internal blackbody, which the chopping mirror samples alternately. If the difference is positive, one reference voltage is added to the signal to be displayed; if negative, another reference voltage is added. This bias change produces a sharp intensity discontinuity in the oscilloscope picture at zero difference between the scene and blackbody signals. The oscilloscope pattern is recorded on film so that the entire 15 to 20 minute picture can be viewed.

The oscilloscope is an extensively modified Tektronix, R5103N mainframe and 5A14N plug-in, plus two other plug-ins which were made by Tetra Tech. The camera is a Tektronix C-50 which uses Polaroid film.

3.2

The digital display unit is a device which displays information recorded by the tape unit. It processes the same signals that the tape unit receives and thereby indicates operation of the entire system. A six position switch and a two position switch select which word of the information block is displayed. The choices for display are 10 μm positive bias, elapsed time, blackbody temperature (internal or external selected by a thermometer switch), mode (sky, sky calibrate, calibrate, or scene), 2.3 micron detector channel, 3.8 micron detector channel, and 10.6 micron detector channel. For the latter three, a two position switch selects scene or blackbody information.

The data come down six lines to the tape unit with a corresponding strobe signal. Each six bit character represents 1/3 or 1/4 of a word. Temperature is a 24-bit word and all others are 18 bits. Data are loaded into three or four six-bit holding registers depending upon the word selected. These registers are strobed by the tape unit strobe gated with the appropriate timing signal. The information loaded into the holding register can be in one of three forms; binary coded decimal (no sign bit), binary with MSB as the sign bit (negative numbers in two's compliment form), and positive binary (no sign bit). Appropriate decoding is performed so that binary coded decimal always enters the display decoder-driver inputs. The display consists of light emitting diodes in seven-segment form (seven pieces of digits).

4.0 CALIBRATION

Calibration is performed with the radiometer looking into the external blackbody. This blackbody is mounted so that the detector sees it through exactly the same optical system as it sees its field of view. By contrast, the purpose of the internal blackbody is to provide the long-term stability required for detection of internal waves; there are only about six of them per hour typically. The internal blackbody in turn is stabilized by a Hewlett-Packard quartz crystal thermometer. As the stable reference, the internal blackbody reduces detector noise and the error caused by any drift in the overall gain. To discuss the latter error, for example, the amplified signal is expressed as a linear function of the radiation B falling on the detector in any of the three bands:

$$S = A + DB \qquad (1)$$

D includes detector sensitivity and amplifier gain, and A the constant voltage in the absence of signal. Taking a difference between this and a similar equation, $S_i = A + DB_i$, for the internal blackbody gives:

$$B = B_i + (S-S_i)/D$$

and the effect of the gain drift on measured radiation B, i.e.,

$$\frac{\partial B}{\partial D} = \frac{S_i - S}{D^2} ,$$

is clearly minimum when $S_i \approx S$, i.e. when B_i is maintained nearly equal to B from the scene.

Radiation from a body is the emissivity ε times the blackbody radiation $B_b(\lambda, T)$ given by the familiar Planck radiation formula and integrated over the band of interest. When only B is measured, we obviously cannot solve the expression

$$B = \epsilon \int_{\text{band}} B_b(\lambda, T)\, d\lambda$$

for both T and ϵ (unless the measurement is made in two bands for two equations, and ϵ is known to be independent of λ; i.e., a grey body). However for water, the principal radiator of interest, ϵ is known and very nearly equal to unity (0.99 to 0.98 in different bands) and so the equation is solved for T assuming ϵ is known. For other objects (especially the sky), one may speak of "radiometric temperature", the temperature that would produce the same radiation if the body were black. Since the temperature changes of interest are small, it is appropriate to expand the blackbody radiation in a Taylor series about a reference temperature T_o, the temperature of the internal blackbody:

$$B = \epsilon B_b,$$

$$B_b \equiv \int B_b(\lambda, T) d\lambda = B_o + C(T-T_o) + C\rho\,(T-T_o)^2 \qquad (2)$$

where $C \equiv \int \left.\frac{\partial B_b(\lambda, T)}{\partial T}\right|_{T_o} d\lambda, \quad \rho \equiv \frac{1}{2C} \int \left.\frac{\partial^2 B_b(\lambda, T)}{\partial T^2}\right|_{T_o} d\lambda$

Usually the quadratic correction $C\rho\,(T-T_o)^2$ is negligible, but its inclusion here will show that it is easy to manage when necessary. Expressed as a percent, ρ gives the percent correction per kelvin. Differentiation of the Planck formula gives the values of ρ, namely

2.3 μm -- 3.3%/K @ 290 K.
3.8 μm -- 1.7
10 μm -- 0.5

As seen through the radiometer optics, there are small but non-negligible losses that reduce the measured radiation to a fraction F of B, and also a small but non-negligible radiance b from the warm window and scan mirror. Incorporating these corrections and substituting equation (2) into (1) gives

$$S_e = A + Db + DF_e[B_o + C(T-T_o) + C\rho(T-T_o)^2],$$

where subscript e is appended to imply external signal (field of view or external blackbody). Note that the only quadratic term in $(T-T_o)$ is in the blackbody function, not in the detector response. Theoretically one expects the detectors to be linear, and tests confirm that they are. Similarly from the internal blackbody $S_i = A + DF_iB_o$. The signal to be used in processing is the difference

$$S \equiv S_e - S_i = \alpha + K\,[T-T_o) + \rho\,(T-T_o)^2] \qquad (3)$$

where $\qquad \alpha \equiv DB_o(b/B_o + F_e - F_i), \qquad K \equiv DF_eC$

It would be convenient if F_i were adjusted so that α vanishes; it is nearly equal to the larger term F_e anyway, and indeed $\alpha = 0$ can be arranged in one of the three bands by changing the iris setting which adjusts the value of F_i. However the losses represented by F_i and F_e are slightly different in the three bands owing to the different paths illustrated in Fig. 3, so it is necessary to tolerate small non-negligible values of α in at least two bands. It is necessary, therefore, to solve equation (3) for two unknown coefficients, α and K by employing the external blackbody at two different temperatures T_1 and T_2. These will always be chosen sufficiently close to T_o to neglect the quadratic term in $(T-T_o)^2$. The two simultaneous equations are, therefore,

$$\begin{cases} S_1 = \alpha + K\,(T_1-T_o) \\ S_2 = \alpha + K\,(T_2-T_o) \end{cases}$$

and the solutions are

$$K = (S_1 - S_2) / (T_1 - T_2)$$
$$\alpha = KT_o + (S_2T_1 - S_1T_2) / (T_1 - T_2) \tag{4}$$

The data-reduction computer program will solve Equation (4) and update the values of the calibration constants K and α every time it reads calibration bits on the magnetic tape. The values of K and α are used to convert the signal S into radiometric temperature T by the following equation which is the solution to Equation (3) to second order in S - α (corresponding to the second order expansion in T - T_o):

$$T = T_o + \frac{1}{K}(S-\alpha) - \frac{\rho}{K}2\ (S-\alpha)^2$$

Usually the last term will be negligible.

The calibration sequence for the radiometer operator consists of four steps separated by 10 to 60 second time lapses when the magnetic tape is turned off. These lapses serve two purposes: to let blackbody servo control reach equilibrium and to identify the sequential steps to the computer as it examines the time words. The four steps are as follows:

1. External blackbody at temperature T_1, mode switch on calibrate, the thermometer selector on internal, detector sees the external blackbody and reads signal S_1, but the precision thermometer reads internal blackbody temperature as usual.

2. Same except thermometer selector on external to read the precise value of T_1 (only known approximately by S_1 in step 1). Voltage data are meaningless since the thermometer cannot control the internal blackbody while reading external.

3. Same as 1 except external blackbody temperature changed to T_2.

4. Same as 2 except thermometer reads T_2 in the external position.

With these values of T_1, S_1, T_2 and S_2, the computer solves the calibration equations as discussed above.